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Boundary layer control as a method of gas turbine blade cooling

Ness, Dwight Osten

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BOUNDARY LAYER CONTROL AS A METHOD
OF GAS TURBINE BLADE COOLING

A THESIS

Submitted to the Graduate Faculty
of the
University of Minnesota

by
DWIGHT O.^{ster} NESS
COMDR. U.S.N.

In Partial Fulfillment of the Requirements
for the
Degree of Master of Science
in
Aeronautical Engineering

August

1949

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дълга сънчева карта.

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ACKNOWLEDGMENTS

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Professors S. J. Robertson, W. A. Hall, T. E. Murphy, and K. E. Neumeier of the Mechanical Engineering Department, for their assistance, advice and suggestions.

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STUDY TO DATE

1965

1967 12.17

Admiringly described

as good by all

except his wife to whom

she was always

misunderstood.

Impressed by

his intelligence

and ability to

communicate

well.

Admiringly

described as a very intelligent

and well educated

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OBJECT AND SCOPE

The object of this thesis was to determine the feasibility of cooling gas turbine blades by introduction of a controlled boundary layer of cool air over the blade surface.

This investigation included a static test of a single instrumented turbine blade in a variable high velocity, high temperature gas stream with variable cooling air flow. Two configurations of the test blade were used to produce variation in boundary layer control.

and enforcement of our rules and by having our
memberships to make certain that there be sufficient
men and men who can be used effectively

in the work of the Association.

Such a situation is not likely to occur if we do not
allow members of the Association to do what
they feel they must do in the interest of their
country and its people.

INTRODUCTION

Maximum effort in the development of gas turbines is being exerted to improve specific power output, to reduce specific fuel consumption and to increase reliability. The most promising field for the attainment of these objectives lies in increasing the turbine inlet temperature which is presently limited by permissible operating temperatures of blading materials. An investigation of the gas turbine thermodynamic cycle reveals the magnitude of improvement possible by increasing turbine operating temperatures. Such an investigation conducted by the NACA (Ref. 1) shows that for a given mass flow of working fluid the specific power output is proportional and the specific fuel consumption is inversely proportional to the inlet temperature. Fig. 1 illustrates this relation.

The increase of turbine inlet temperature, however, is limited by high temperature strength of blade materials. The development of high temperature metals is proceeding, but at a slow rate. How slowly metallurgical progress has been made is shown in Fig. 83 of Ref. 2. Allowable blade temperatures advanced from 1180° F. in 1935 to 1200° F. by 1940 and to 1365° F. by 1945. The rate of increase has been no greater since 1945.

Non-metallic materials such as ceramics have yet to demonstrate their adaptability to the rigorous service

requirements of turbine blading. As a result the use of some method of cooling the gas turbine blading presents itself as the method of allowing higher gas temperatures with present materials.

Several methods of blade cooling have been proposed and evaluated. A discussion of these methods as related to this thesis follows.

Late model German turbojet engines such as the Juno 004 employed hollow turbine blade cooled internally by means of air blown into the root and exhausted at the tip. 1650° F. turbine inlet temperature was used with 7% of compressor air output required to cool blades approximately 400° F.

The NACA has proposed (Ref. 1) an improvement to this method by inserting a core in the blade, leaving a small annular air passage. It was found that the heat transfer from blade to cooling air was principally in the boundary layer and adjacent cooling air so the insert permitted similar cooling with less air flow. Fig. 2 graphs the results of this improvement.

Another cooling method consists of circulating water through internal passages in the blade. This system of cooling has accomplished very large blade temperature reductions. German applications (Ref. 3) conducted by Dr. Schmidt permitted $850-930^{\circ}$ F. blade temperatures with a gas temperature of 2200° F. Fig. 3 shows an NACA analytical

investigation of water cooling which also gave considerable blade temperature reduction. It must be pointed out that while water cooling is very effective, the problems of handling the high temperature, high pressure water flow at high rates makes service application of this method difficult.

A modification of the foregoing system, known as rim cooling, has also been tried. Here water is circulated through the rotor rim so as to extract heat from the blade root. Less temperature reduction is obtained and the disadvantages of the water coolant system still exist. Fig. 4 shows rim cooling effectiveness. It can be seen from the figure that having a blade material of high thermal conductivity, K_M , is essential to this method.

All of the foregoing methods employ the same basic principle of cooling. They do not inhibit the heat transmission to the blade, but do increase the internal conductivity, or removal of heat, thereby affecting cooling. The proposal of this thesis is to substitute a boundary layer of cool air over the blade's surface in order to inhibit the heat transmission from the hot gases to the blade.

A coating of high temperature ceramic of low conductivity would embody this same principle. Fig. 5 shows the effectiveness of ceramic coatings of various thicknesses. While this is a very promising field insofar as temperature of operation is concerned, the inherent defects of brittle-

unpublished data on the effects of various types of environmental
pollution on the breeding of some 300 molluscan species found
in addition to, although not all, species which often
inhabit similar environments such as marshy and gullied
areas. Results have been obtained with respect to

Довжина складу відповідає 10-15 см.

Thus this system makes it difficult for the firm to find and hire qualified workers who are willing to work at reasonable wages. This is because the firm has to pay higher wages than its competitors. The firm also has to pay higher taxes due to the high cost of labor.

ness, thermal shock sensitivity and low tensile strength have obviated service use of ceramic covered blading.

If a region of low thermal conductivity can be interposed between the gas and the blade, then the objective of blade cooling could be accomplished. The natural boundary layer on the blade is such a region. However, the natural boundary layer forms at the temperatures of the gas. In this experiment the use of relatively cool air from the engine compressor is suggested to form a lower temperature boundary layer.

The justification of this idea is based on one of the fundamental laws of heat transfer, Faurier's equation for conduction (Ref. 4). (Experience has shown radiation effects to be secondary). Stated mathematically for steady state conduction:

$$q = KA \frac{dt}{dx}$$

where q = rate of heat transfer.

K = coefficient of thermal conductivity.

A = crosssectional area of path.

$\frac{dt}{dx}$ = temperature gradient in direction of heat flow per unit distance.

This law shows that for a given configuration the rate of heat transfer from gas to blade may be made by reducing K and/or $\frac{dt}{dx}$.

K for air is reduced by reducing temperature.

This is shown mathematically from Larchens equation:

disparis alienus und hinc *Apodanum* omnes tangunt, unde

and the other two were to be sold at a loss.

different functions may distinguish us from man and monkeys. In our present

To sum up based on our results to date and from the literature, we can conclude that the main mechanism of action of the studied compounds against *S. Typhimurium* and *S. Enteritidis* is probably through inhibition of the synthesis of the bacterial cell wall.

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DOI 10.1215/03616878-33-3-701 © 2008 by the Southern Political Science Association

1000 m. de Marcahuasi se via a una localidad que se conoce como

and the staff at the most relevant point to place

disturbing evidence of human life on Earth.

Am J Appl Physiol. 1997; 83(4 Pt 2):1400-1406.

$$K = K_{32} \frac{492 + C}{T + C} \left(\frac{T}{492} \right)^{3/2}$$

where T = absolute temperature

C = constant (.0129 for air).

K_{32} = K at 32° F.

The temperature gradient from the boundary layer to blade, $\frac{dt}{dx}$, is reduced by the use of the cool air controlled boundary layer. In fact, the cool air boundary layer will at first be lower in temperature than the blade so that the blade will transfer heat to the boundary layer. However, the temperature gradient from the hot gas to the boundary layer would be increased so it would be rapidly heated. The optimum configuration might therefore require a series of bleeds from the blade so the average temperature of the layer along the blade would be minimized.

In the author's experience a controlled boundary layer has been successfully employed to cool a liquid rocket nozzle. In 1936 the author collaborated in the construction of a liquid rocket motor in which a boundary layer of coolant air bled into the nozzle enabled prolonged operation. The nozzle was of mild steel yet endured the very high temperature rocket exhaust gases better than any contemporary nozzles of superior materials.

Internationalization & T-translation

• 陈和山《碧鸡漫录》卷之二

Figure 2 shows a range of negative correlations with the first two PC's and no significant correlation with the third PC. This indicates that the first two PC's represent the main variance in the data set. The first PC is highly correlated with the first three variables (Table 2), which are all related to the water balance of the catchment area. The second PC is highly correlated with the fourth variable, which is the water balance of the lake. The third PC is highly correlated with the fifth variable, which is the water balance of the river. The fourth PC is highly correlated with the sixth variable, which is the water balance of the sea.

TEST EQUIPMENT

Fig. 5 shows the complete test equipment layout schematically. The test blade was mounted in a closed test section supplied with hot gas from a single J-33 combustion chamber. Fig. 6 is a photograph of the test section mounted on the burner. Air was supplied to the burner from the compressor of a naturally aspirated Allison V-1710 engine, Fig. 7. The quantity of gas flow was regulated by throttling the Allison engine while its temperature was controlled by burner fuel pressure. The temperature of the blade was measured by two thermocouples. All control and measurement was done from the control panel adjacent to the gas turbine test cell. Fig. 8 is a photograph of the control panel. The air which formed the controlled boundary layer was supplied from the laboratory air main at regulated pressure. The quantity of cooling air was measured in a standard design sharp edged orifice meter, shown in Fig. 9.

The test blade was manufactured from a solid June 004 turbine blade. Availability was the reason for selection of this blade. The "tinidur" type alloy (30% nickel, 14% chrome, 1.75% titanium, 1.2% carbon, balance, iron) possessed very difficult machining properties and low thermal conductivity. The blade roots were cut off flat for convenient mounting and the tip shortened by 3/4 inch

Ammerlandse kust vallen niet alleen aan de zuidkant van de Eemshaven maar ook aan de noordkant van de Eemshaven. De kustlijn loopt vanaf de monding van de Eems tot aan de monding van de IJssel. De kustlijn is ongeveer 100 km lang en bestaat uit verschillende delen. De belangrijkste delen zijn de Oostkust, de Westkust en de Zuidkust. De Oostkust is de langste kustlijn en loopt van de monding van de Eems tot aan de monding van de IJssel. De Westkust is de middelste kustlijn en loopt van de monding van de Eems tot aan de monding van de IJssel. De Zuidkust is de kortste kustlijn en loopt van de monding van de Eems tot aan de monding van de IJssel. De belangrijkste delen van de Oostkust zijn de Eemsdelta, de Eemshaven en de Eemshoof. De belangrijkste delen van de Westkust zijn de IJsseldelta, de IJsseloog en de IJsselsehoofd. De belangrijkste delen van de Zuidkust zijn de IJsseldelta, de IJsseloog en de IJsselsehoofd.

because of space limitations in the test section.

For the first test, configuration A was manufactured. In this blade the cooling air supply hole was drilled up the blade from root to 1/4 inch of tip through the thickest section. This hole was .20 inch in diameter. The air bleed holes (1/16 inch) were drilled from blade surfaces joining the supply hole. They were placed at a 45 degree angle with blade surface. There were six bleed holes to each surface. The exits were ground out with a fish tail countersink pattern to distribute the bleed air spanwise. A .15 inch hole was drilled up the leading edge for location of the thermocouple tip at midspan. The trailing edge was too thin to permit similar treatment so a 3/32 inch hole was drilled chordwise at midspan to snugly hold a thermocouple bead. The thermocouple was lead in in a stainless steel tube one inch downstream and bent 90 degrees and cemented in the trailing edge hole. Figs. 12, 13 and 14 show the thermocouple mounting. Fig. 10 shows the A blade between a standard blade and a shortened standard blade. The boundary layer is introduced at approximately the 30% chord point.

Configuration B blade is shown in Fig. 11. The boundary layer air supply was introduced through a .15 inch drilled passage 1/4 inch behind the leading edge. A 60 degree included angle slot was milled down the length of the leading edge and 3/32 inch bleed holes drilled joining the

...and the first step in this direction is to make the
entire system a self-sustaining one.

and the right of made of sugar & water.

supply passage. In this design the cooling enters the slot opposed by stagnation pressure and flows out of the slot on both edges, forming the boundary layer.

The test section consisted of the blade mounting block shown in Fig. 13, and two side plates made of six inch channel. The bottom was closed with a 1/2 inch plate so that the hot gases which entered at the top were constrained to exhaust through the open side. The entrance and exit dimension are 3.5 x 4.5 inches. Fig. 12 pictures the complete test section. Fig. 14 shows another view of the blade mounting block. The test blade is centrally located with two parallel mounted standard blades to guide the flow.

Temperatures of the test blade were measured by 20 gauge chromel-alumel thermocouples which read on a Brown recorder. The small size thermocouples provided fast response and use of standard sillimanite insulations in the blade. The insulators were ground slightly in diameter for mounting in blade. The thermocouple tips were firmly seated in 3/32 inch holes for maximum sensitivity to blade temperatures. The trailing edge thermocouple bead was buried completely to insure it would sense blade, rather than gas temperatures.

Compensated lead wires connected the thermocouples to the selector switch for the recorder to eliminate errors in readings by variation in ambient temperature. The gas

For the first time, we can see the results of our work in a single place, and it's a great way to showcase our progress and achievements.

the 2000-2001 school year, and again in 2001-2002. The first two years were spent at the University of Alberta, while the third year was spent at the University of Guelph. In 2002-2003, he began his Ph.D. at the University of Alberta, and graduated in 2006. He has been a postdoctoral fellow at the University of Alberta since 2006.

іде вимушене зробити певні дії що не відповідають
масові але єдність сільськогосподарської економіки та земель
всіх селян відчуває недовіру до влади та чиновників
та відсутність якості якісної роботи що викликає
задовільність від функціонування постійної земельної
послуги та земельного реєстру які виконують земельні
послуги та земельний реєстр відповідно до закону та
законодавчих актів та земельного реєстру та земельної
послуги та земельного реєстру відповідно до закону та
законодавчих актів та земельного реєстру та земельної

הנתקה מהתפקידים הדרושים לשליטה על אמצעי התקשורת. מכאן, מושג של "טוהר" או "טוהר ואמון" מתייחס לא רק לשליטה על אמצעי התקשורת, אלא גם לשליטה על כל אמצעי תקשורת.

temperature entering the test section, T_4 , was measured by a radiation shielded chromel-alumel thermocouple.

to determine what a fit, malignant, and well-motivated individual
is likely to do. In this paper we will focus on the

second point, and we will argue that it is important to distinguish between two types of individuals who are likely to commit crimes. One type of individual is one who has been socialized to believe that certain actions are acceptable or even desirable. This individual may be a member of a group that believes in the right to self-defense, or he may be a member of a group that believes in the right to privacy. The other type of individual is one who has been socialized to believe that certain actions are unacceptable or even undesirable. This individual may be a member of a group that believes in the right to equality, or he may be a member of a group that believes in the right to freedom.

The first type of individual is more likely to commit crimes because he has been socialized to believe that certain actions are acceptable or even desirable. He may be a member of a group that believes in the right to self-defense, or he may be a member of a group that believes in the right to privacy. The second type of individual is less likely to commit crimes because he has been socialized to believe that certain actions are unacceptable or even undesirable. He may be a member of a group that believes in the right to equality, or he may be a member of a group that believes in the right to freedom.

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TEST PROCEDURE

The temperature of the test blade was read with and without cooling air flow under exactly similar flow conditions. This technique permitted comparison of the two temperatures obtained to show the blade reduction due to cooling air alone.

The Allison engine was first started and its speed set to obtain the desired flow rate of burner air. The flow rate was measured by means of the pressure drop across the orifice in the compressor inlet duct.

Next, combustion was initiated in the burner with the spark and acetylene flare and fuel pressure adjusted until desired gas temperature obtained. When conditions stabilized temperatures and pressures were recorded. During runs with cooling air, the flow rate was varied in increments of 1/10 inch of water and temperature recorded when stabilized.

In order to investigate the cooling effects over a broad range of gas velocities three settings of the Allison engine were used to give low, medium and high gas flow rates. However, the low flow rate is not included in this report as it was unrealistically low compared with actual turbine operation. The flow rate was below minimum idling rate for a J-33 engine.

and the author has been unable to find any reference to this in the literature.

Следует отметить, что все эти правила приложены к реальному миру, а не к фантастическому. Поэтому вспомогательные правила должны быть сформулированы так, чтобы они соответствовали реальной жизни. Для этого необходимо учесть следующие факторы:

1990. *Ministeria* *gazetted* *off* *exempted* *as* *policy* *of*
- *not* *to* *qualify* *small* *mining* *and* *oil* *mining* *permits* *as*
and *right* *for* *mining* *and* *permits* *as* *large* *mining* *operations*
in *valley* *and* *area* *not* *more* *than* *100000* *hectares*
area *mining* *and* *permits* *not* *to* *apply* *to* *small* *mining*
minerals *within* *any* *area* *more* *than* *100000* *hectares*
and *not* *to* *apply* *to* *mining* *and* *permits* *within* *area*

TEST RESULTS

The results of the experiment are contained in tables I and II and the graphs, Figs. 16 through 19. The graphs are plotted to show temperature reduction versus weight of cooling air flow.

These graphs are similar in shape and show that the reduction in blade temperature was approximately twice as great in the leading edge as the trailing edge. This is to be expected because of the increase in boundary layer temperature resulting from heat transmission from the gas. Also, the thinness of the blade section near the trailing edge offers more resistance to heat flow internally.

The graphs also show that the temperature reduction rate is greatest (the slope is maximum) at low cooling air rates. This is evidence that the boundary layer is established at low flow rates and is effective in reducing heat transfer. Beyond a flow rate of .2 lb./min. most of the graphs become straight line functions. This apparently results from thickening of the boundary layer and shows the insulating effect is proportional to the thickness. This effect conforms with Fourier's law. The cooling effectiveness, particularly at low flow rates, is greater with this method than the method of Fig. 2.

To illustrate the cooling effectiveness consider the J-33 turbojet engine. Maximum cooling of 280 F. at 1600 F. gas temperature could be accomplished with only 2% of compressor air.

Configuration A produced more uniform results than those of configuration B, as can be seen by comparing Figs. 16 and 17 with 18 and 19. Configuration A curves plotted more parallel and gave results proportional to gas temperature, while configuration B curves intersect and are out of order with gas temperature increments. Configuration A probably gave more uniform boundary layer formation, since the flows were convergent rather than opposed. It was calculated that the stagnation point on the leading edge would fall in the milled slot so the cooling air would spill over both surfaces of the blade and form good boundary layers. From the non-uniform results at different flow rates stagnation point shifting may be indicated. Also, turbulence in the test section may have prevented uniform boundary layer formation and promoted mixing. It is believed that had the blade been manufactured with boundary layer control slots of the type used in airplane practice, much higher quality results would have been obtained. This type bleed was considered but discarded because of the machining problems, which would have required machining beyond shop capacity.

Uncontrollable variation in the speed of the Allison engine contributed to inaccuracy of data. A "hunting" of about fifty RPM occurred during much of the running, which produced 500 RPM variations in compressor speed. The variation in burner air flow caused drifting of gas temperatures.

Comparison of Figs. 16 with 17, and 18 with 19, shows cooling effectiveness variation with gas flow rate. Cooling effectiveness is greater at the lower flow rate. This is consistent with the laws of heat transmission by convection. The heat transfer from gas to blade increases with velocity.

From all graphs, the blade temperature reduction is shown to increase with gas temperature. This, also, is compatible with the laws of heat transfer, the $\frac{dt}{dx}$ term of Fourier's equation increases so more heat is transferred to the outer boundary layer. But, the heat transfer to the blade through the laminar sublayer is of such small magnitude that the net effect is greater blade temperature reduction.

near the image axis at smaller separations

«... «*жизнь*» въ приспособлении къ будничнымъ бытскимъ потребамъ и въ съданіи съѣзда Академии наукъ 1911 г. въ «*жизни*» писателей и писательницъ 1911 года. Каждому изъ писателей, писательницъ и писателю-женщинѣ предъложено напечатать въ «*жизни*»

адар тој ће бити највероватнији узимајући у обзир да је уједно и један од најважнијих аспеката који се у овој ситуацији појављују.

и в то же время не отрицать, что в этом есть что-то неизвестное и неожиданное.

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al quale giaceva l'attualità più diffusa e più ampia ed era quasi il più avanzato dato che mai era stato pubblicato.

Correspondence to Dr. David Breslow, Department of Environmental Health Sciences, School of Public Health, University of Michigan, Ann Arbor, MI 48104-2025.

Since more than 50 percent residual acid byproduct should still remain after the initial treatment, the acid solution should be

CONCLUSIONS

In view of the limited scope of the experimental tests, no detailed quantitative conclusions can be drawn. However, the results obtained from the foregoing tests do support the following general conclusions:

1. The introduction of a boundary layer of relatively cool air on a turbine blade in a high temperature, high velocity gas stream inhibits the transmission of heat from the gas to the blade, more than through the natural boundary layer, and results in reduction of blade temperature.
2. The magnitude of the reduction in blade temperature is proportional to the weight flow of air introduced into the boundary layer up to the limit investigated of 2% of the gas flow in an equivalent full scale engine.
3. This method of blade cooling is feasible insofar as weight flow of cooling air required to accomplish useful blade temperature reduction is concerned.

the following year or sometime after that.

the date of the above

is not known.

introduction will be made available and the major oil

company of the continental United States will be asked to furnish
to effect plans which will meet the needs of all companies
in the field. The executive committee of the American
Water Works Association will be appointed to be responsible for

the preparation of a plan which will be submitted to the State
and the National Water Commission for consideration and
advice. This committee will consist of one representative from
each company which is to be represented by the American
Water Works Association.

and should be submitted with the accompanying letter.

Letter addressed to each director and to the executive committee of the American
Water Works Association. The letter should be dated January 1, 1912, and should be addressed to the
executive committee of the American Water Works Association. The letter should be dated January 1, 1912,
and should be addressed to the executive committee of the American Water Works Association.

TABLE I

OBSERVED TEST DATA

HIGH AIR FLOW RUNS

COMPRESSOR RPM - 24,000
— GAS TEMPS —

COOLING AIR ΔP "H ₂ O	W _a	800°F		1000°F		1200°F		1400°F		1600°F	
		T _{BLE}	T _R								
0	0	785	785	995	995	1190	1195	1390	1340	1585	1585
.1	.217	720 65	760 25	920 75	965 30	1110 80	1150 45	1255 135	1325 65	1440 145	1615 70
.2	.345	710 75	755 30	920 75	965 30	1070 120	1135 60	1255 135	1325 65	1440 145	1595 80
.3	.471	700 85	750 35	895 100	950 45	1050 140	1135 60	1220 170	1310 80	1385 200	1480 105
.4	.600	690 95	735 50	875 120	945 50	1030 160	1110 85	1200 140	1300 70	1350 235	1465 120
.5	.726	675 110	730 55	855 140	937 58	1015 175	1115 80	1185 205	1290 100	1335 250	1450 135
.6	.846	665 120	730 55	850 145	930 65	1015 175	1115 80	1160 230	1210 100	1320 265	1450 135

CONFIGURATION A

RUN 1

CONFIGURATION B

RUN 2

0	0	755		755		945		975		1150	
		T _{BLE}	T _R								
.1	.217	725 30	750 5	915 30	965 10	1080 70	1120 30	1300 25	1318 12	1350 130	1440 35
.2	.345	695 60	735 20	900 45	955 20	1075 75	1120 30	1230 15	1310 20	1330 150	1440 35
.3	.471	670 85	720 35	875 75	945 30	1042 107	1120 30	1200 125	1310 20	1310 170	1465 50
.4	.600	650 105	720 35	855 90	935 40	1035 115	1120 30	1160 165	1295 35	1390 180	1425 50
.5	.726	640 115	715 40	825 120	920 55	1000 150	1115 35	1135 190	1290 40	1270 210	1430 55
.6	.846	640 125	715 40	800 145	905 70	1010 215	1275 55	1255 225	1420 55		

P _f	PSI	800°F		1000°F		1200°F		1400°F		1600°F	
		T _{BLE}	T _R								
W _f	lb/hr	67	76	84	96	107	129	127	146	107	
ΔP _{E.A.}	"hg	1.83	1.82	1.80	1.65	1.60	1.55	1.50			
W _{B.A.}	lb/sec	2.85	2.845	2.83	2.71	2.71	2.59				
P ₃	"hg	14.8	15.0	16.1	17.1	17.1	16.8				
P _{t3}	"hg	15.4	15.4	16.5	17.5	17.5	17.2				
P ₄	"hg	.72	.64	.60	.52	.52	.50				
P _{t4}	"hg	11.45	11.8	13.1	13.75	13.75	13.8				
g	"hg	10.63	11.16	12.5	13.23	13.23	13.3				
M _f		.731	.75	.795	.82	.82	.823				

TEMP: COOLING AIR - 80°F
AMBIENT (T.CELL) 120°FPRESS: ATMOS - 29.82 "hg
AMBIENT (TEST CELL) - 27.50 "hg

OBSERVED TEST DATA
MEDIUM BURNER AIR FLOW RUNS
COMPRESSOR RPM - 13,250

-16-

TABLE II

COOLING AIR ΔP "H ₂ O	W _a	800°F				TEMPS				1600°F			
		T _{BLE}	T.R.	T _{BTE}	T.R.	T _{BLE}	T.R.	T _{BTE}	T.R.	T _{BLE}	T.R.	T _{BTE}	T.R.
0	0	777	765	945	1000	1115	1290	1370	1315	1535	1510		
.1	.217	720	57	750	35	912	73	103	31	1052	143	1135	65
.2	.345	710	67	750	35	815	100	150	50	1040	153	1121	13
.3	.471	695	82	750	35	860	135	140	60	1035	160	1160	80
.4	.600	675	12	750	35	850	145	740	60	1015	150	1160	60
.5	.726	610	197	750	35	835	160	740	60	1010	185	1120	50
.6	.846	555	122	750	35	825	170	740	60	785	210	1120	30
.7	.972	550	127	750	35	815	180	740	60	775	220	1160	50
.8	1.07	645	132	750	35	800	195	730	70	765	230	1120	80
0	0	720	725	730	745	1142	1147	1325	1320	1490	1480		
.1	.217	645	75	706	11	807	170	130	15	1042	100	1120	21
.2	.345	640	80	700	25	850	130	125	20	1030	114	1120	21
.3	.471	632	88	790	25	831	193	725	20	1015	167	1110	31
.4	.600	625	75	700	25	825	205	725	20	1000	142	1100	41
.5	.726	605	115	675	30	800	230	715	30	105	111	1075	52
.6	.846												
.7	.972												
.8	1.07												

INSUFFICIENT COMPRESSED AIR SUPPLY

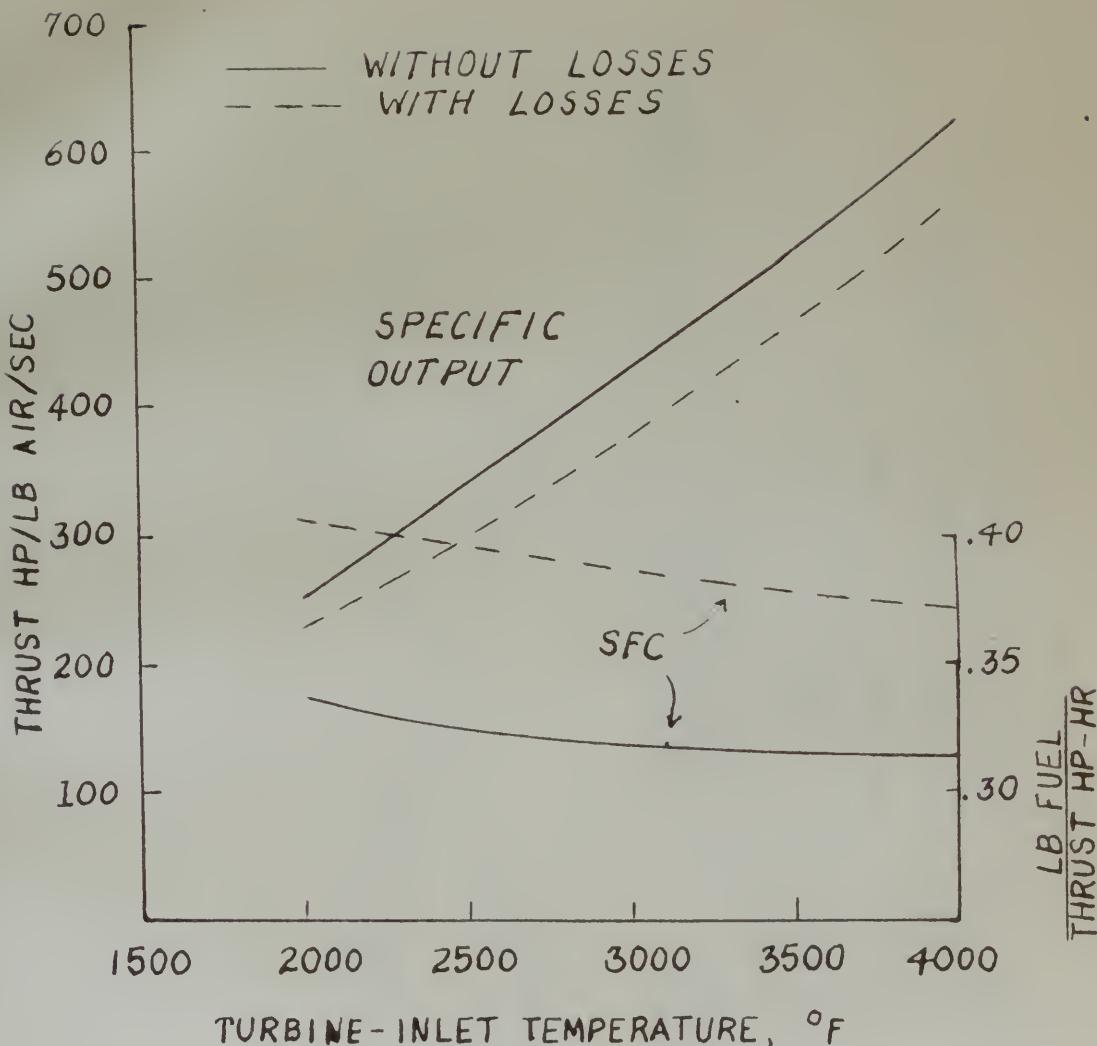
A
CONFIRMATION
CONFIRMATION

		800°F	1000°F	1200°F	1400°F	1600°F
P _t	PSI	47	61	67	73	79
P _t	lb/in ²	47	65	80	90	103
DP _{B.A.}	" _{in}	1.05	.75	.88	.83	.80
WB.A.	lb/sec	2.16	2.06	1.18	1.12	1.07
P ₃	" _{H₂O}	7.1	7.8	8.4	8.6	9.1
P _{T3}	" _{H₂O}	8.3	8.0	8.0	8.1	8.3
P ₄	" _{H₂O}	.8	.55	.4	.32	.30
P _{T4}	" _{H₂O}	5.8	5.3	5.55	6.45	7.35
P ₈	" _{H₂O}	5.1	5.25	5.15	5.05	5.05
M _t		1.717	1.500	1.551	1.515	1.600

TEMPS : COOLING AIR 80°F
AMBIENT TEST CELL 120°F

PRESS : ATMOSPHERIC
AMBIENT TEST CELL

21.82 "_{H₂O}
24.50 "_{H₂O}



TURBOPROP ENGINE PERFORMANCE WITH + WITHOUT COOLING LOSSES. AIRPLANE SPEED, 500 MPH: MACH NO., 0.69; ALTITUDE 30,000 FT. (Ref. 1)

Fig. 1

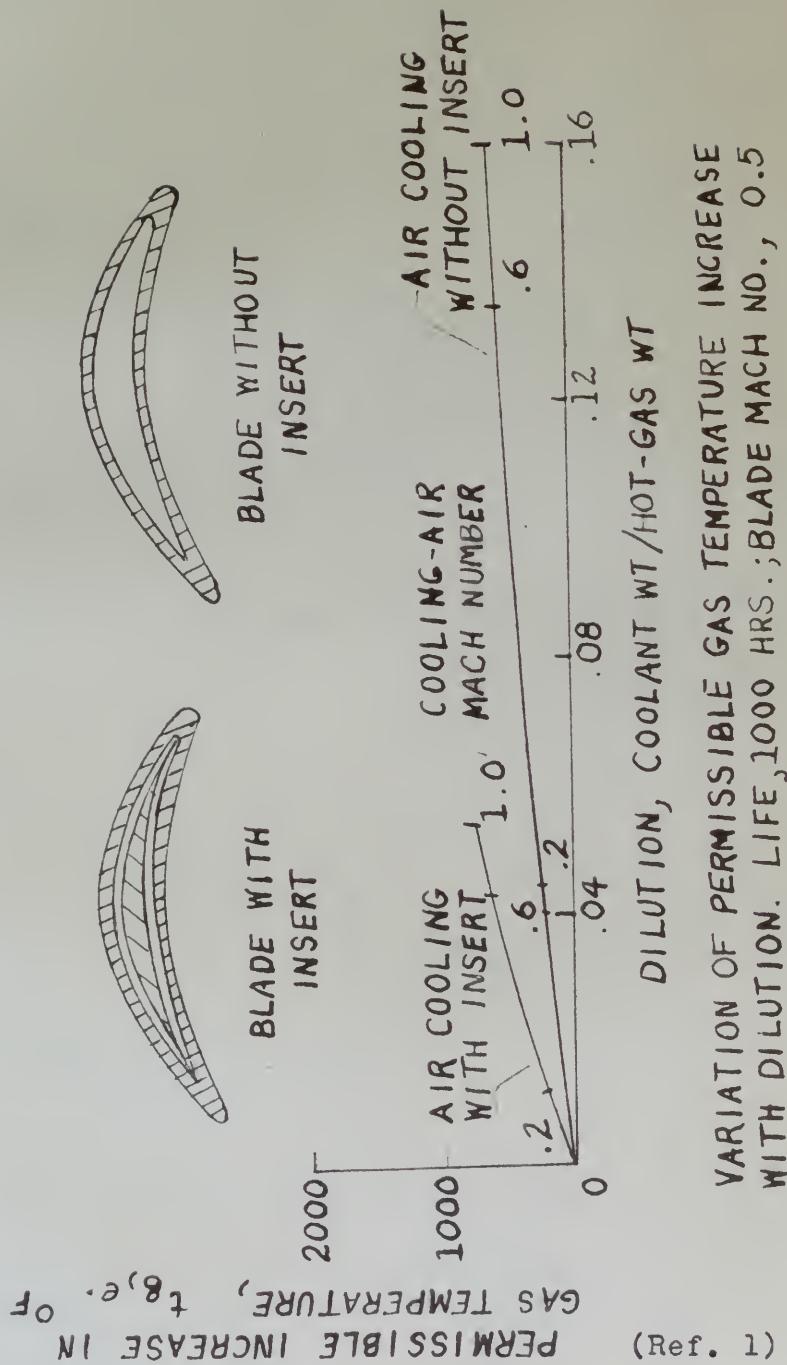
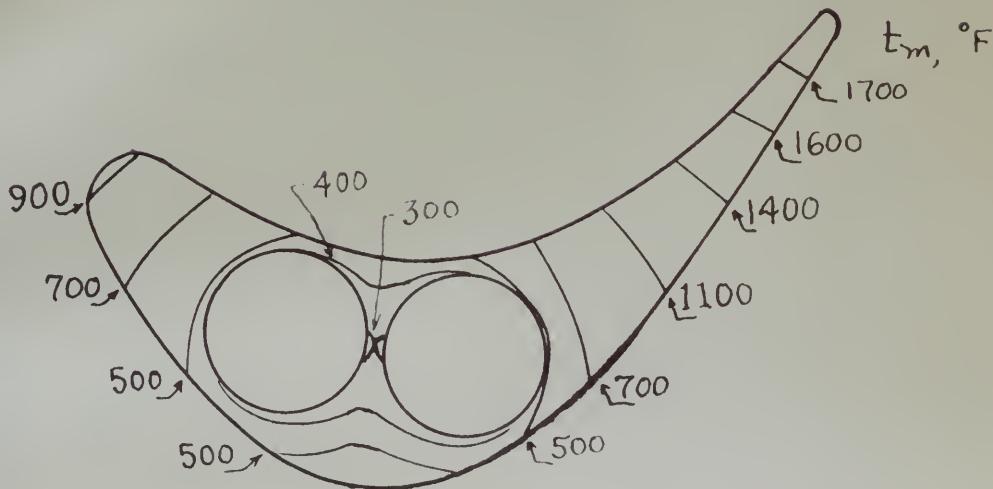
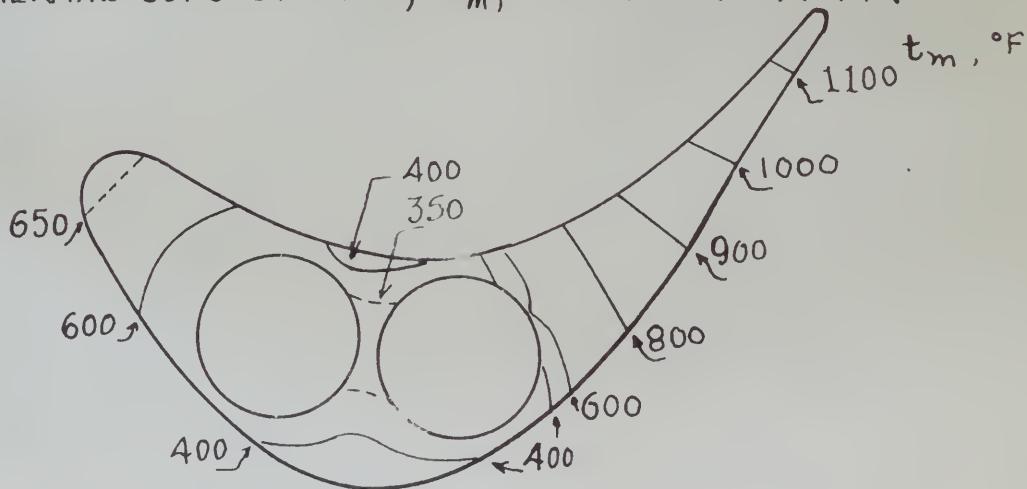


Fig. 2

THERMAL CONDUCTIVITY, k_m , 15 BTU/(HR)(°F)(FT)



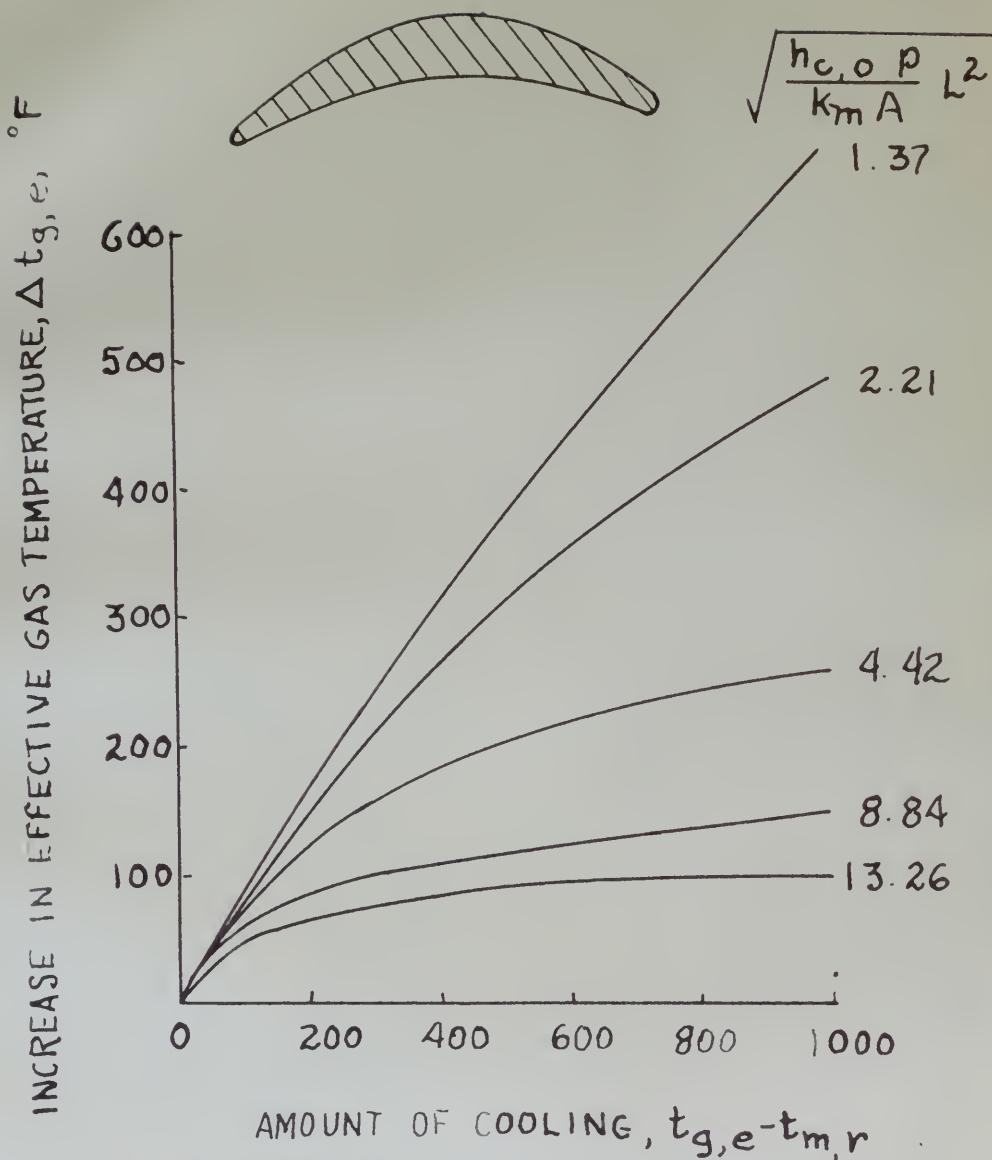
THERMAL CONDUCTIVITY, k_m , 100 BTU/(HR)(°F)(FT)



ISOTHERMS IN BLADE SECTIONS OF DIFFERENT CONDUCTIVITY MATERIAL WITH LIQUID COOLING. GAS FLOW, 55 LB/SEC; WATER FLOW, 6.42 LB/SEC; GAS TEMPERATURE, 2000° F; WATER TEMPERATURE, 200° F.

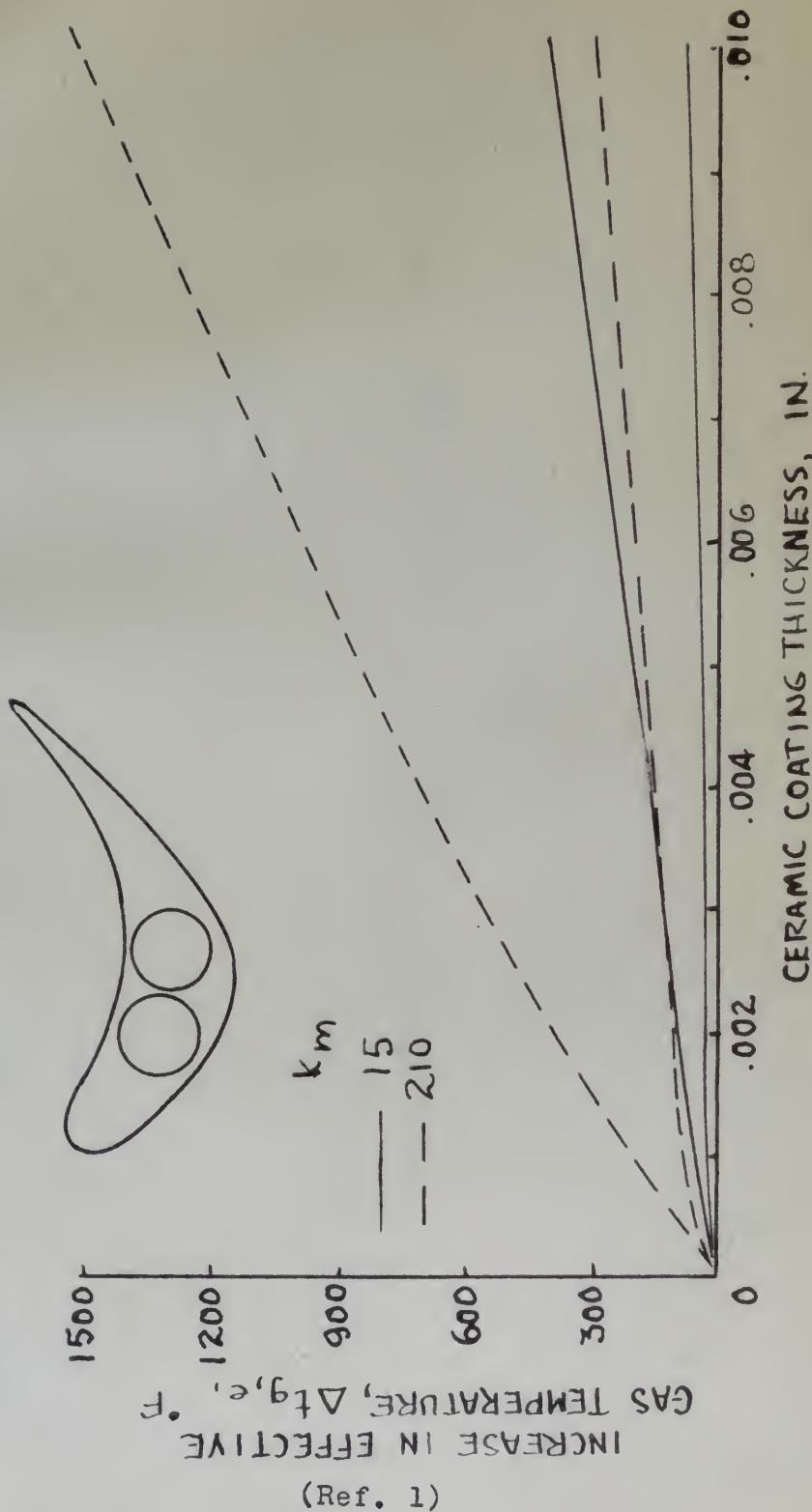
(Ref. 1)

Fig. 3



VARIATION OF RIM COOLING EFFECTIVENESS.
MAXIMUM ALLOWABLE MACH NUMBER, 0.5.
(Ref. 1)

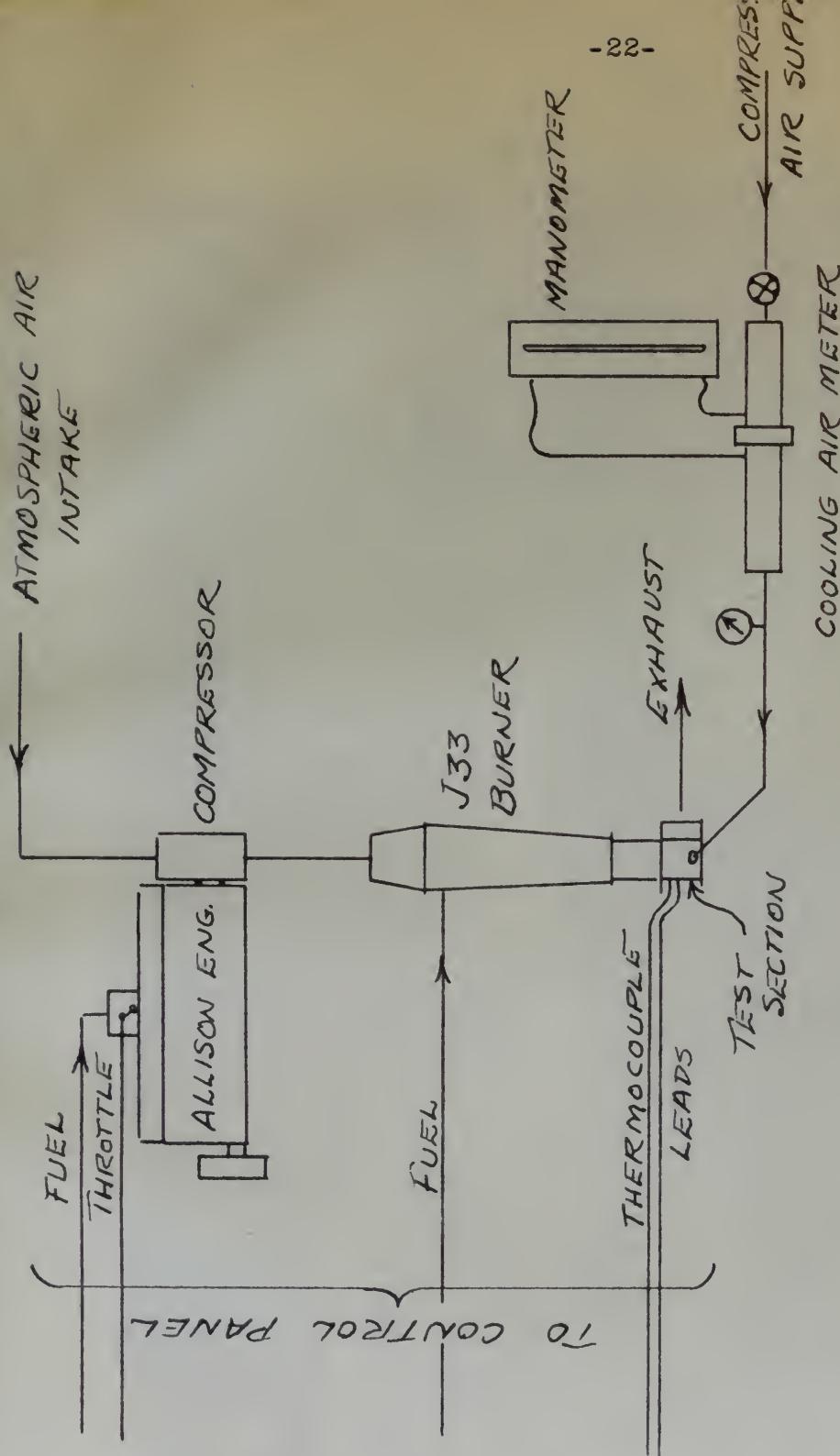
Fig. 4

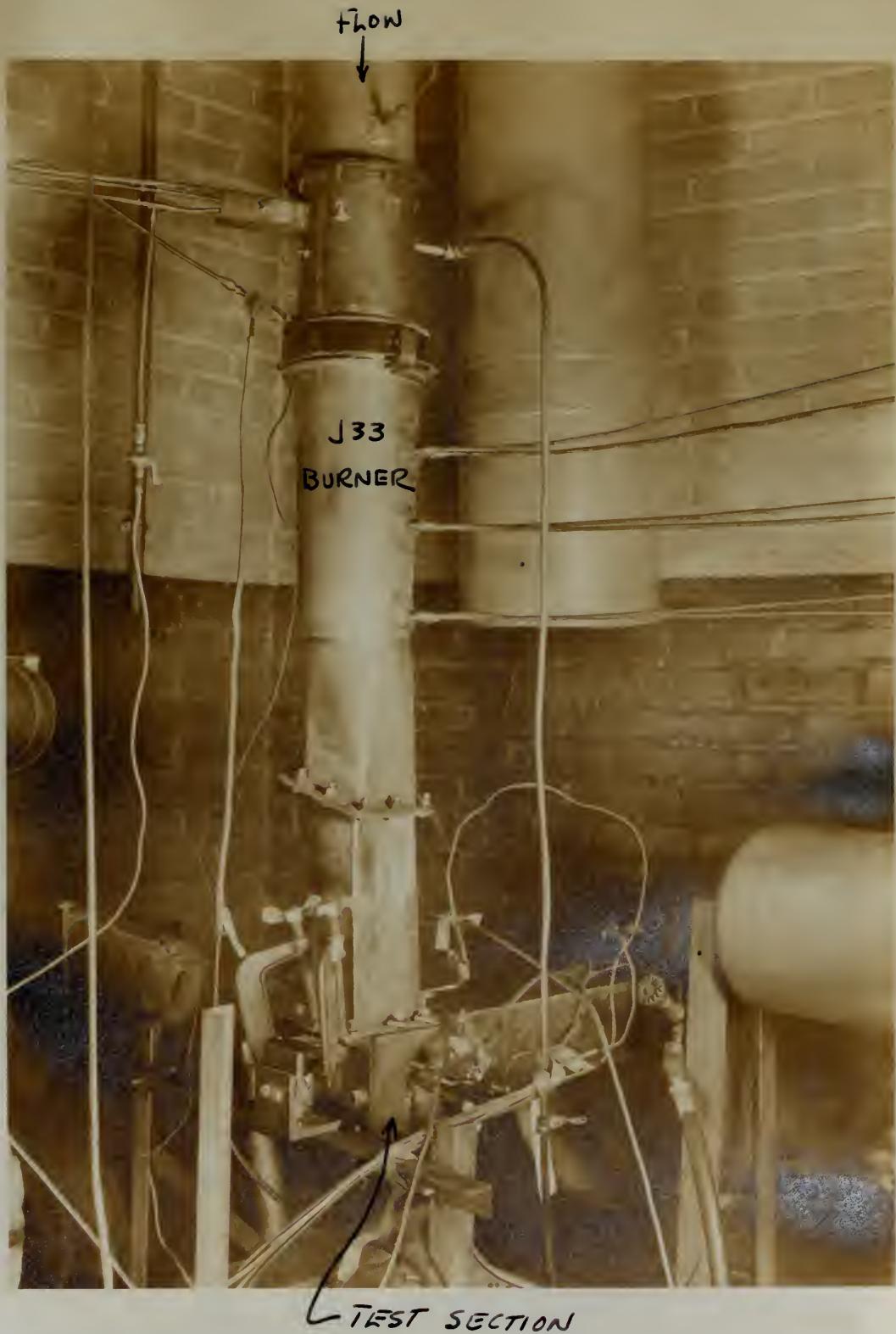


VARIATION OF INCREASE IN EFFECTIVE GAS TEMPERATURE WITH CERAMIC COATING THICKNESS FOR TWO METAL AND CERAMIC THERMAL CONDUCTIVITIES.

Fig. 5

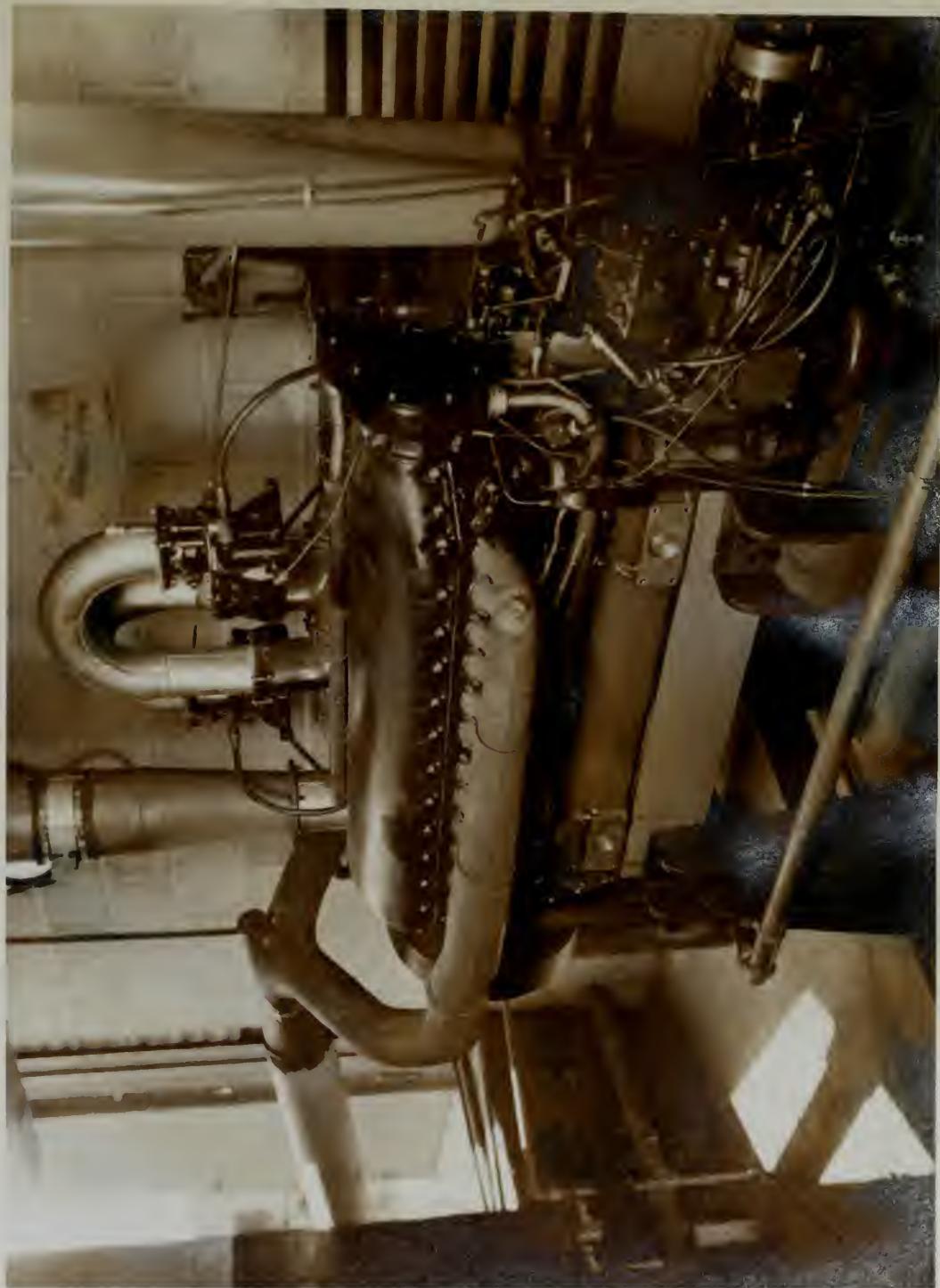
SCHEMATIC DIAGRAM OF COMPLETE TEST LAYOUT





TEST SECTION MOUNTED ON BURNER





Allison Engine



CONTROL PANEL

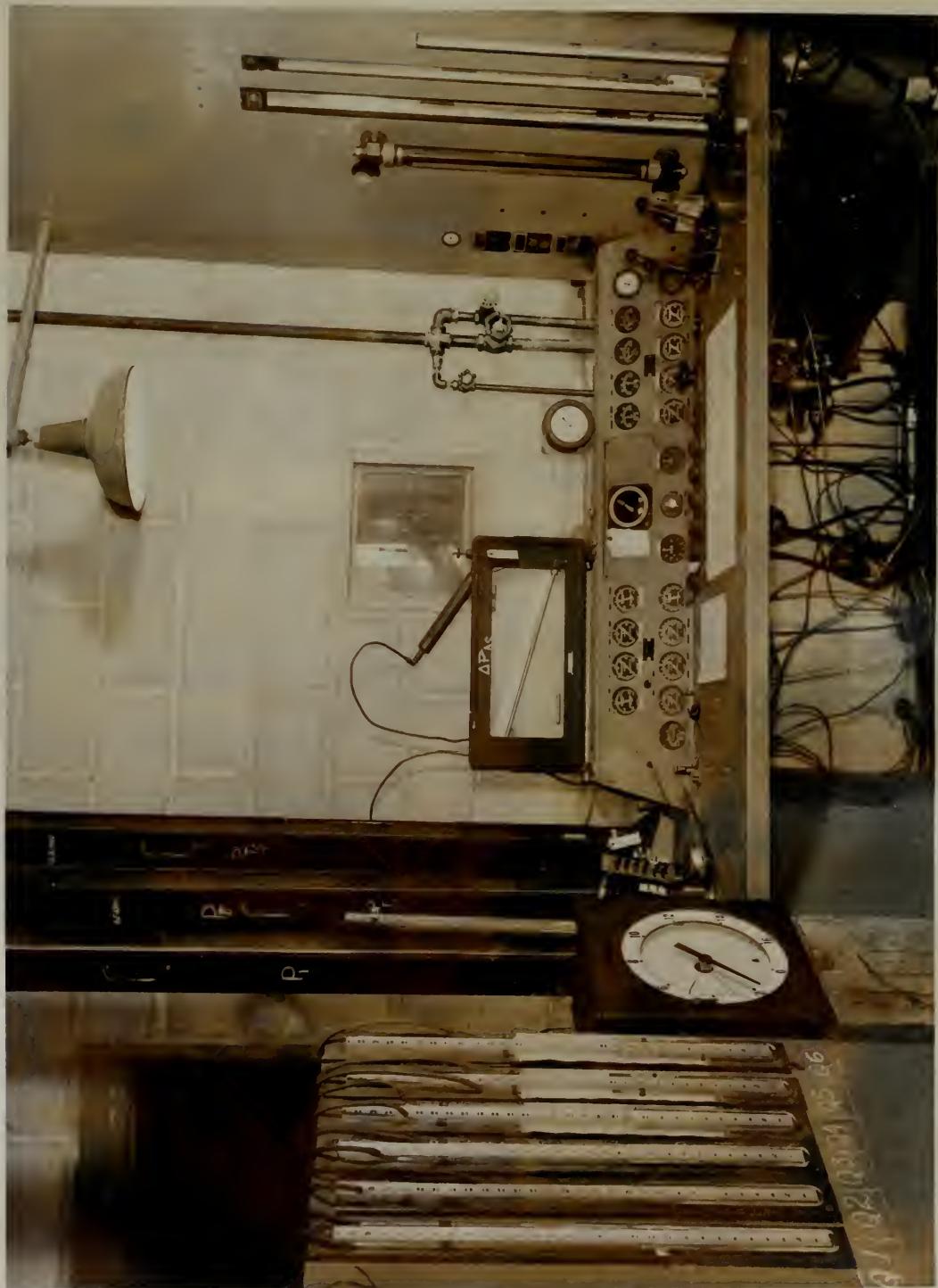
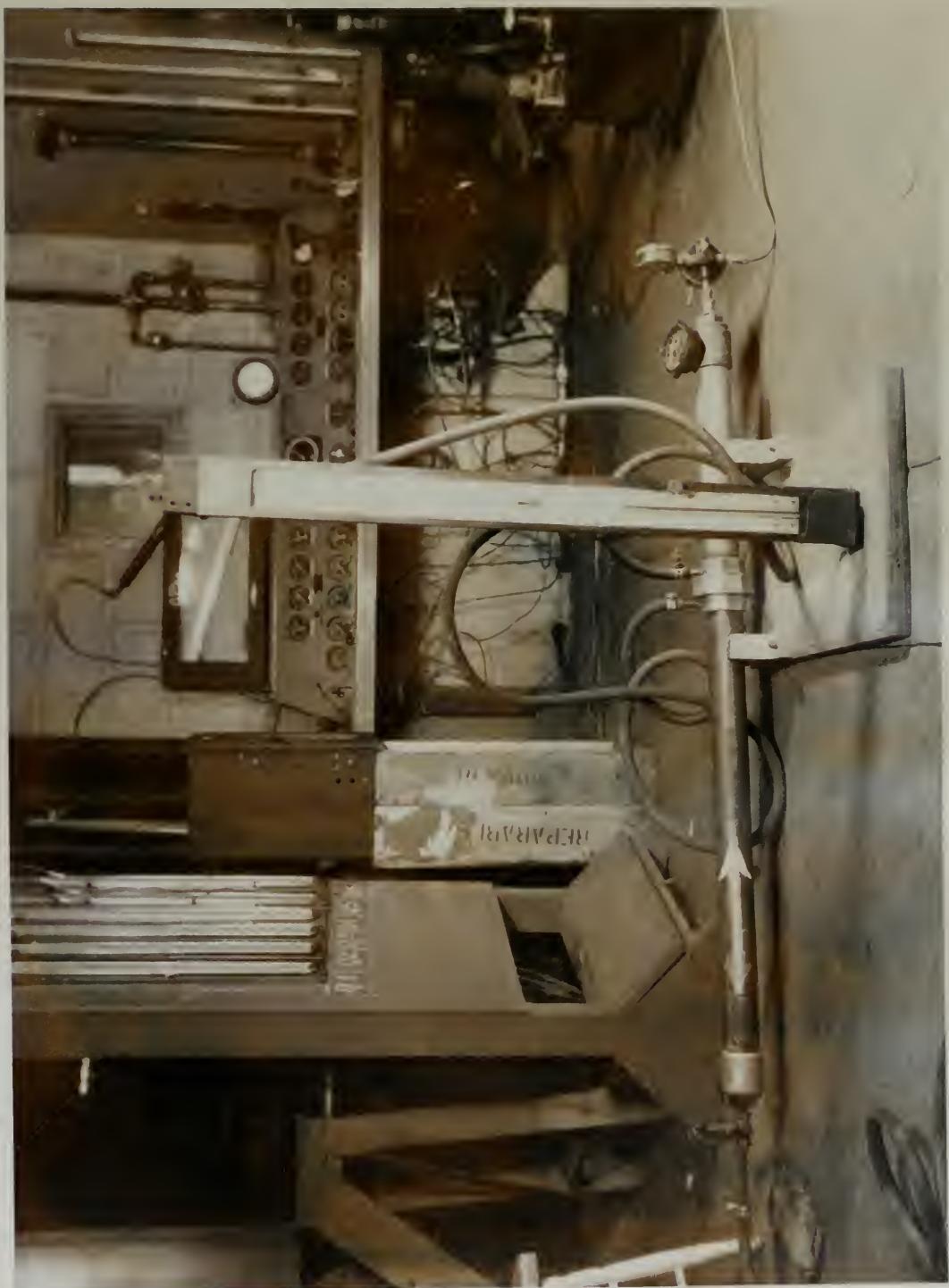


Fig. 9





COOKING AIR METER

Fig. 10

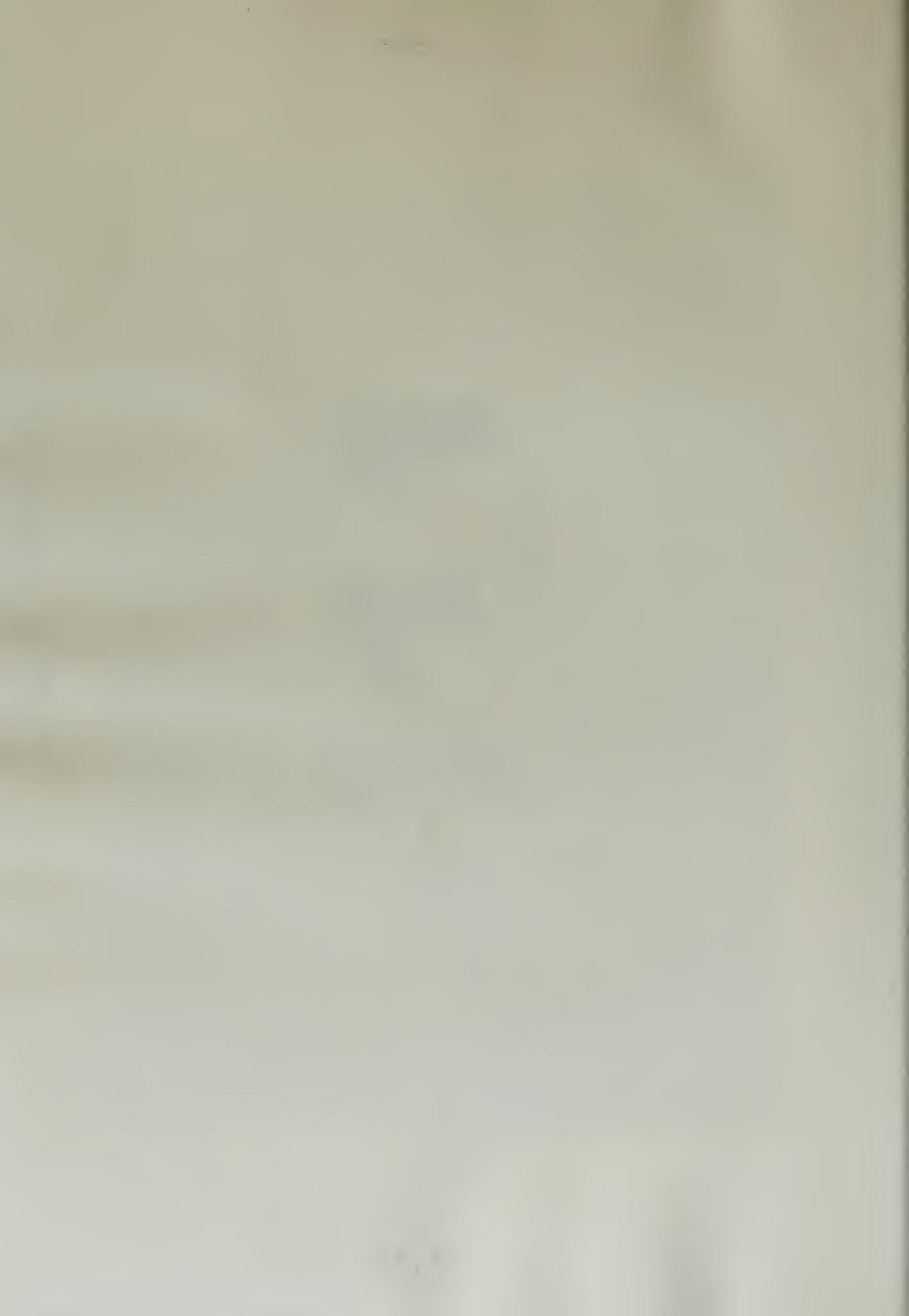


TEST BRADLE (CONF. A)



AIR BLEEDS

STANDARD
BRADLE



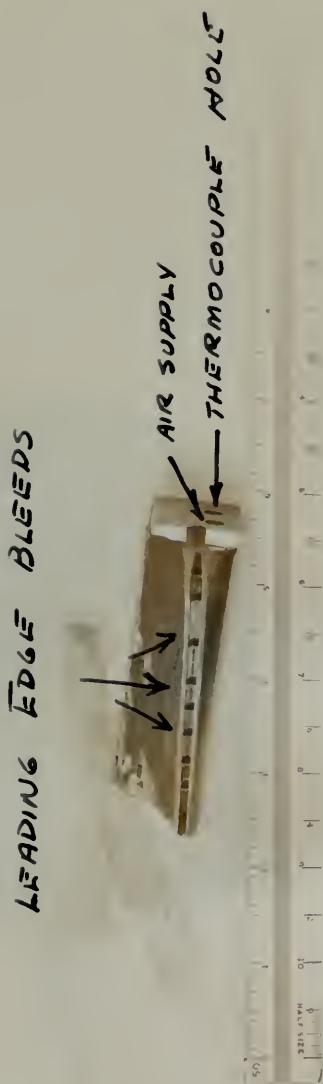


Fig. 12

TEST BLADE (CONF. B)

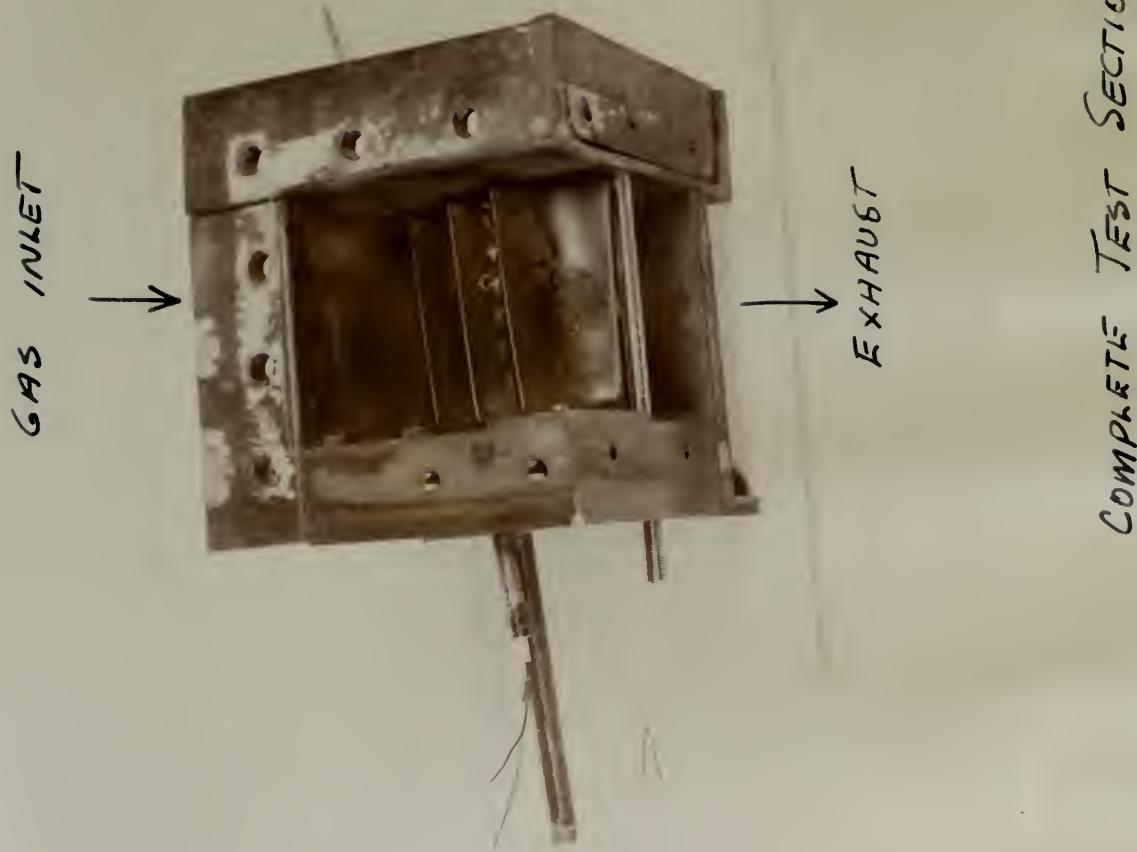


Fig. 13

COMPLETE TEST SECTION

MOUNTED TEST BLADE



- A - LEADING EDGE
THERMOCOUPLE
- B - TRAILING EDGE
THERMOCOUPLE
- C - COOLING AIR SUPPLY
- D - " " BLEEDS

END VIEW OF BRADES



Fig. 15

CONFIGURATION A

BURNER AIR FLOW 155 to 170 lb/min
MACH NO ≈ .77

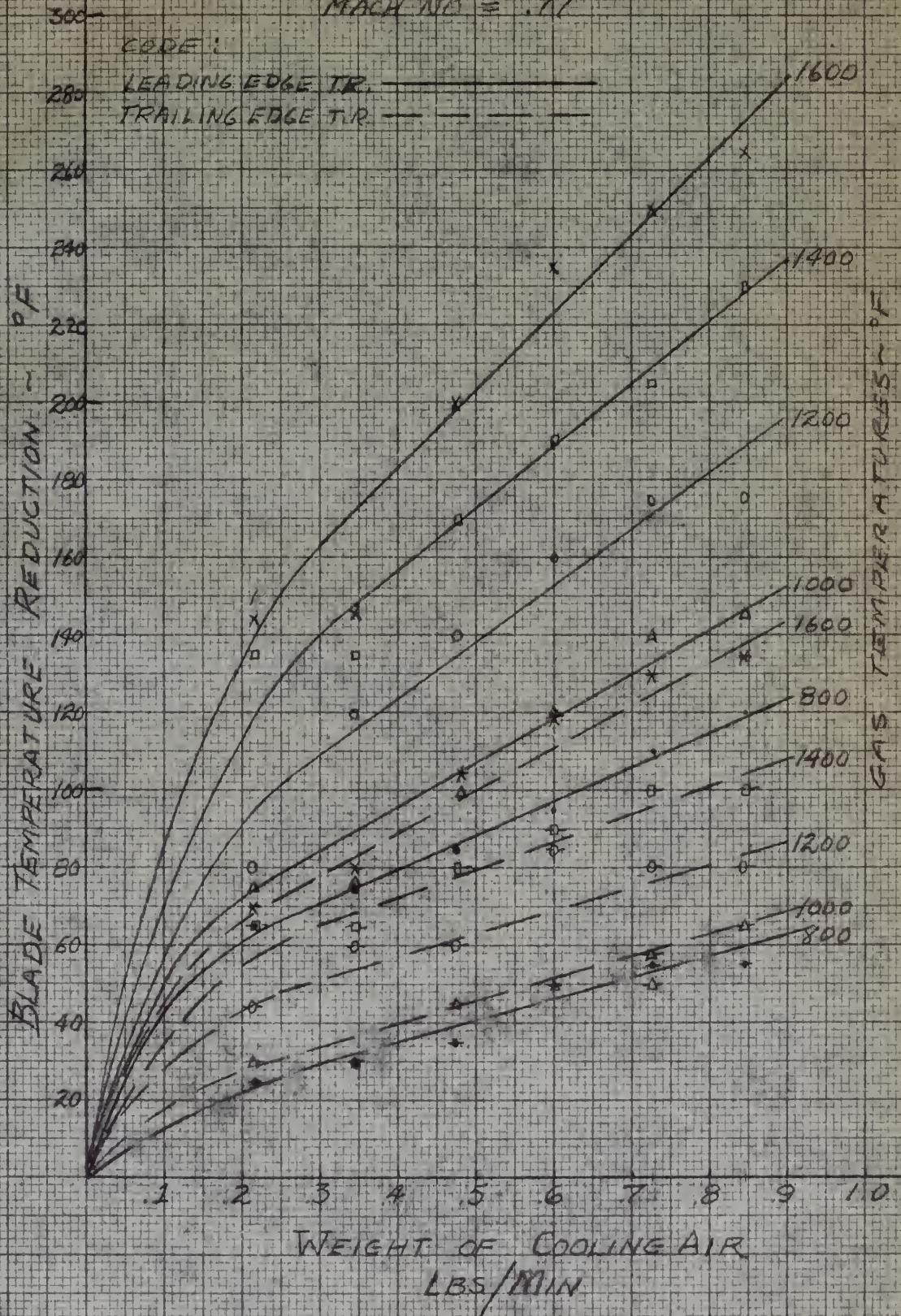
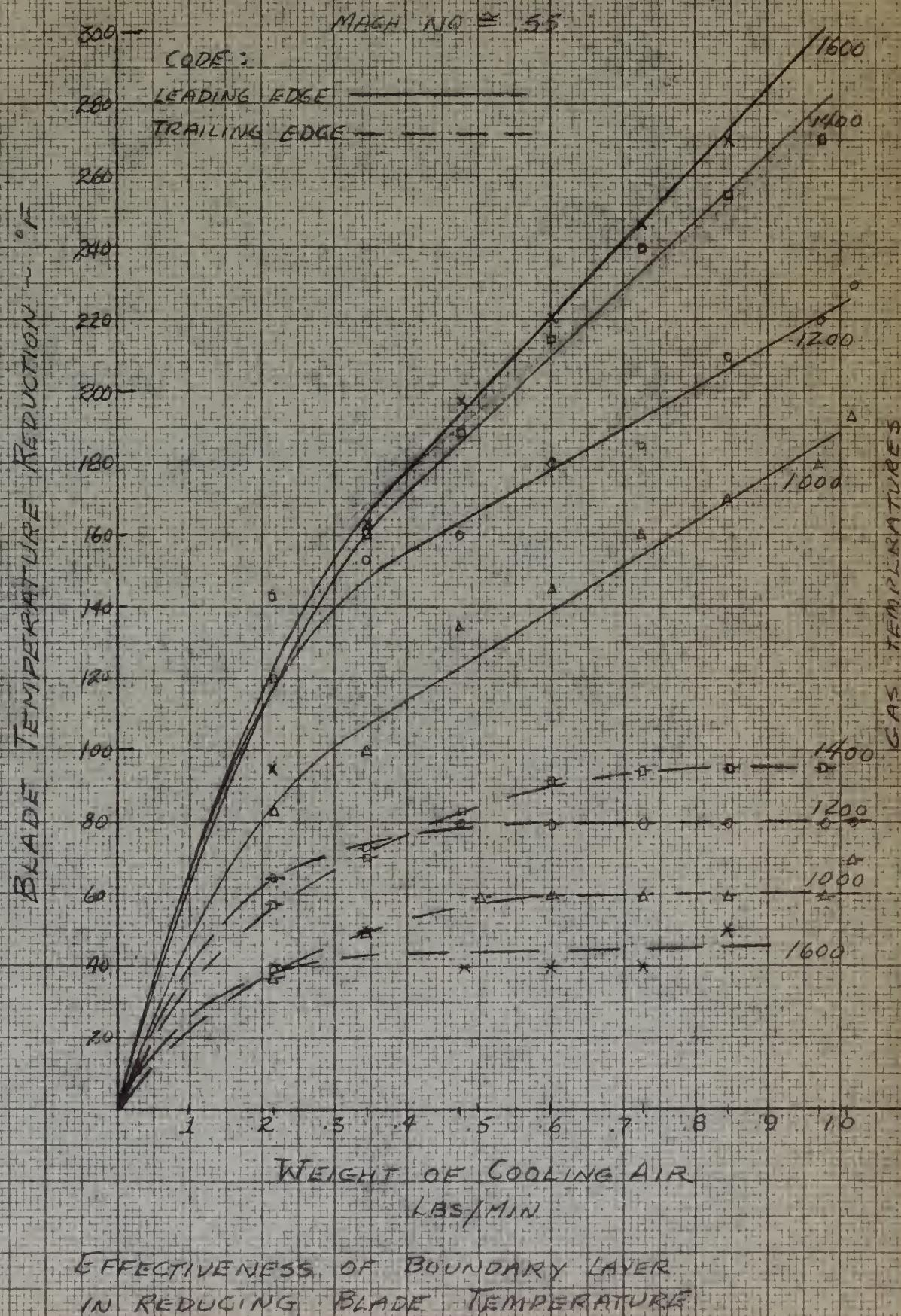


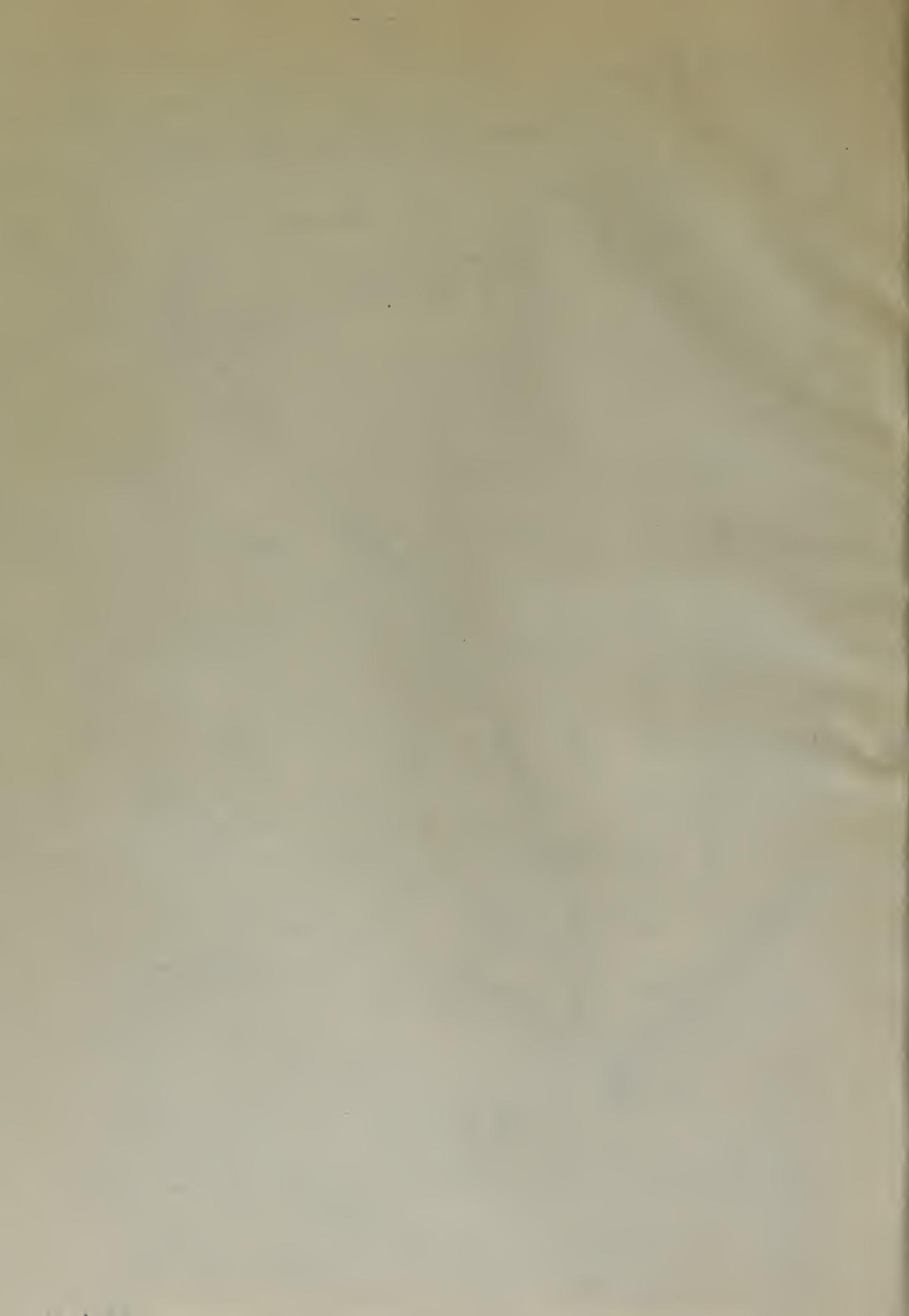
FIG. 16

CONFIGURATION A

BURNER AIR FLOW - 108 to 130 LBS/MIN

MACH NO = .55

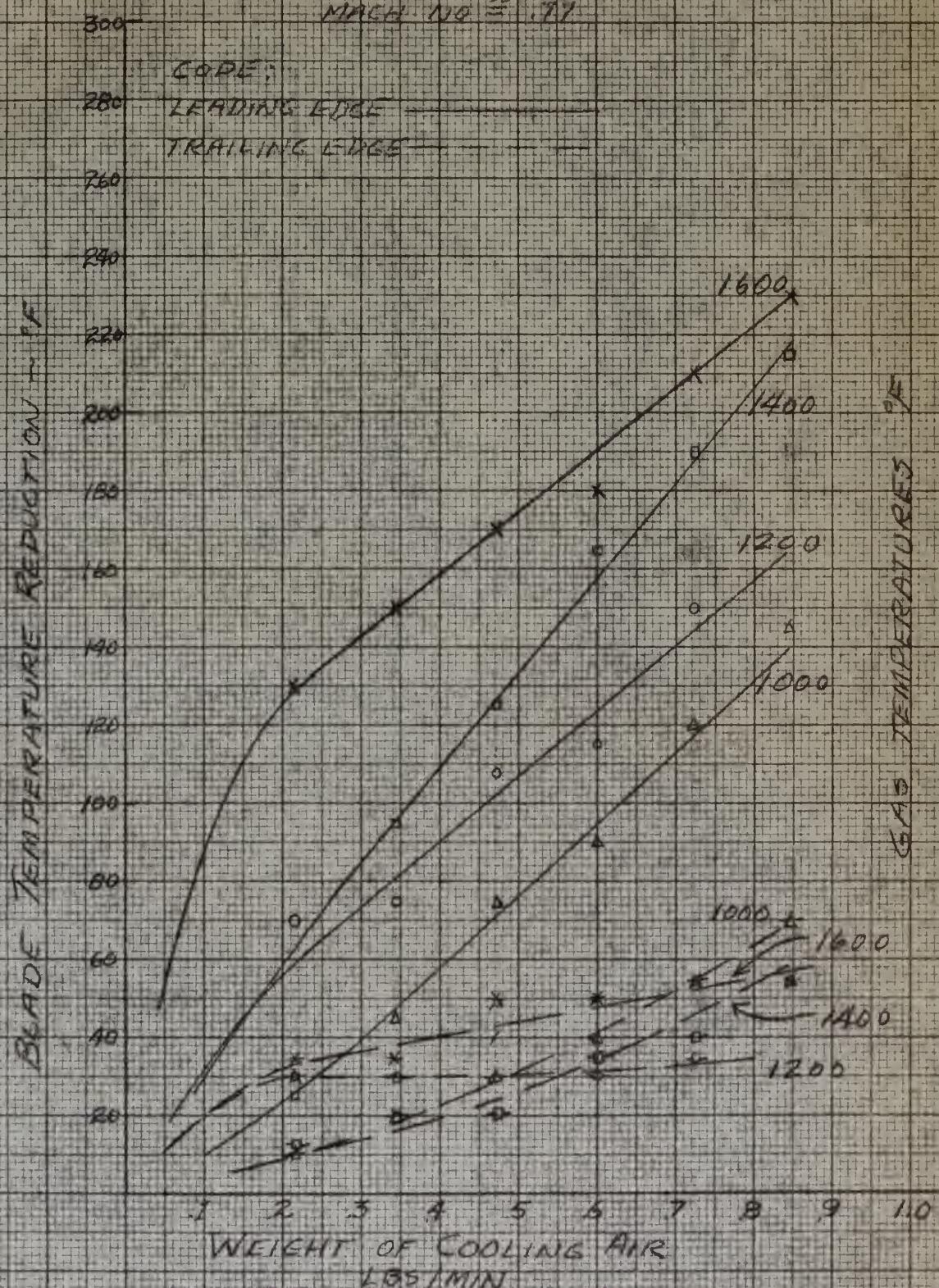




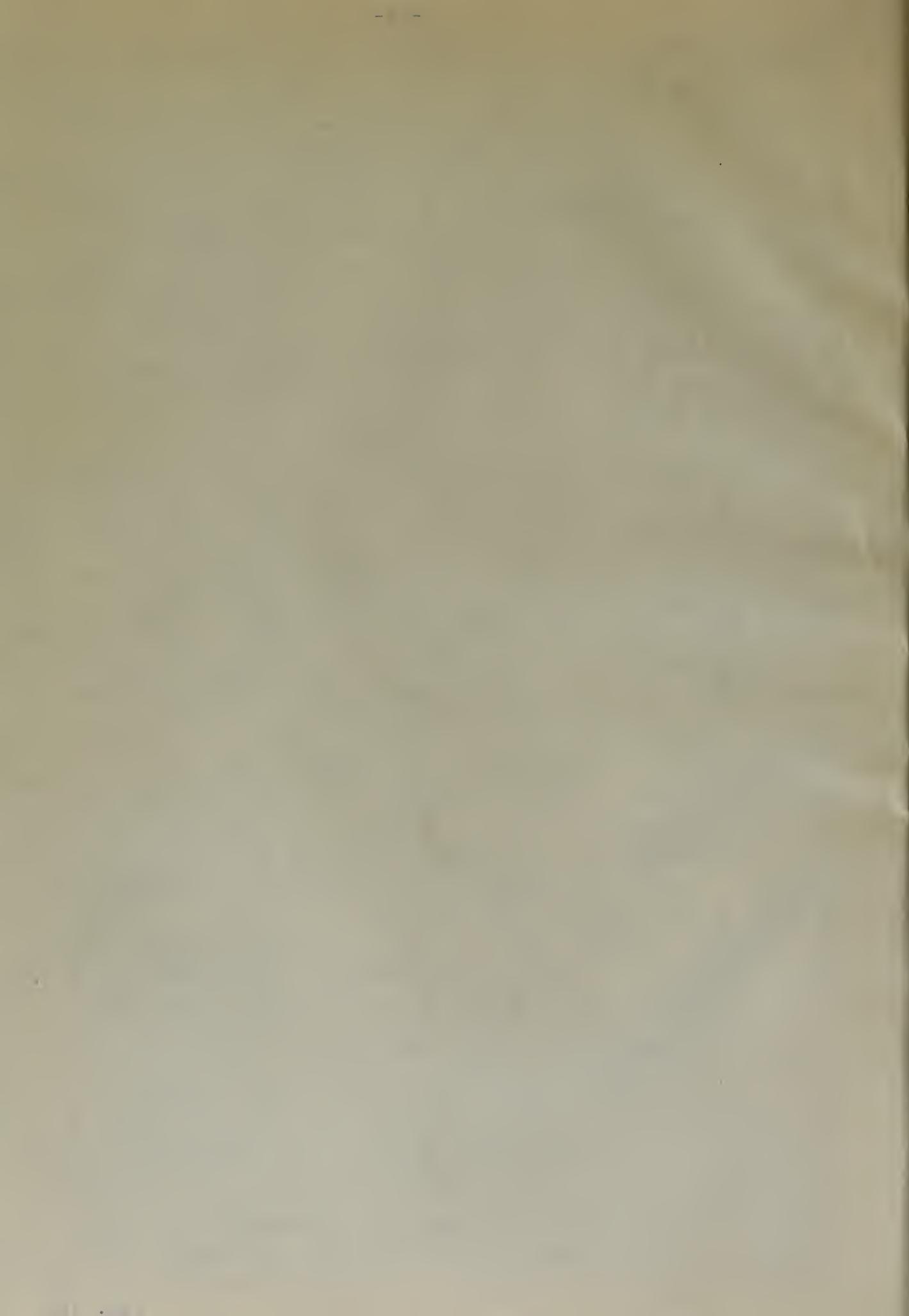
CONFIGURATION B

BURNER AIR FLOW = 155-170 l/min

MARCH 19 1971



EFFECTIVENESS OF BOUNDARY LAYER IN REDUCING BLADE TEMPERATURES



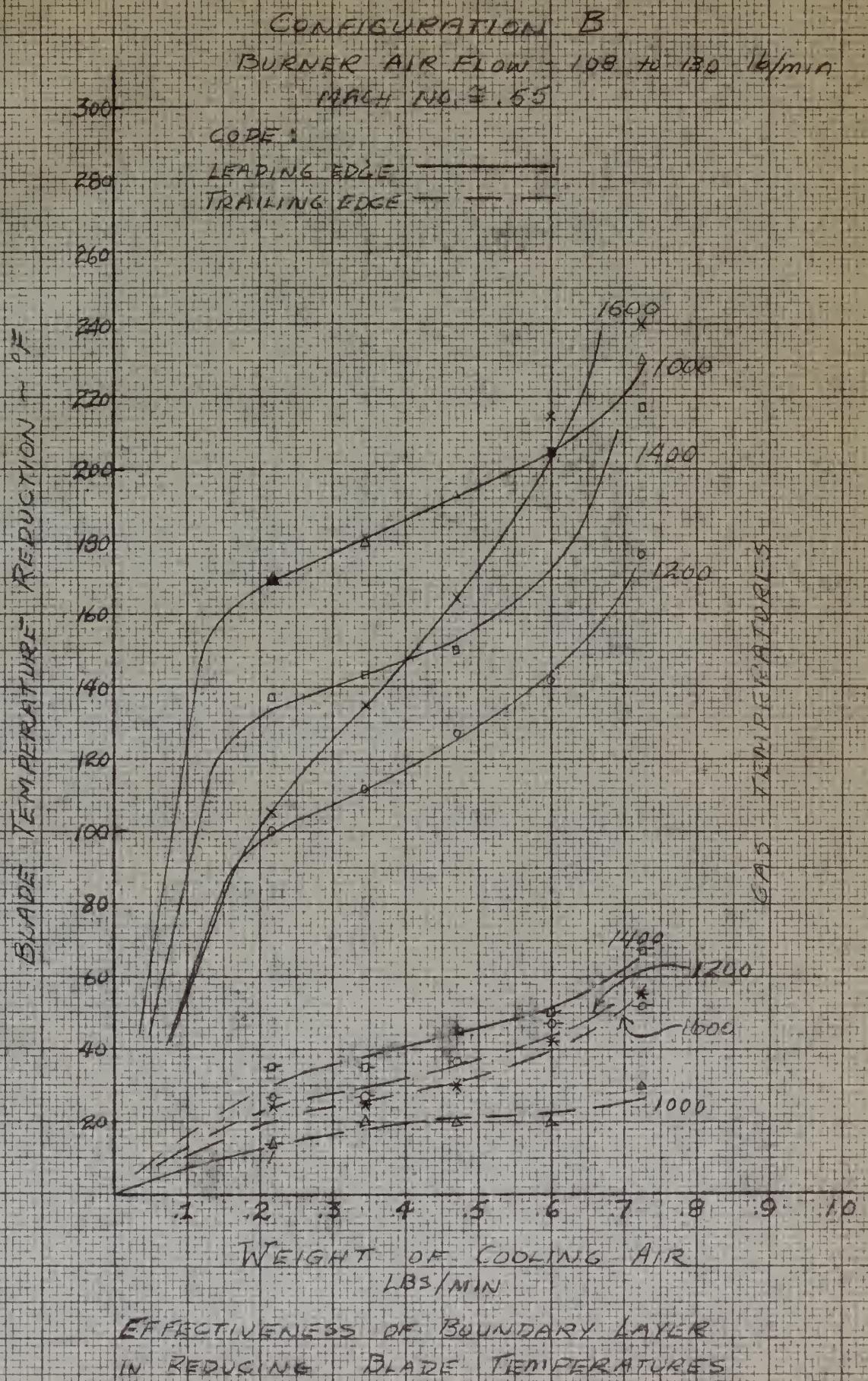
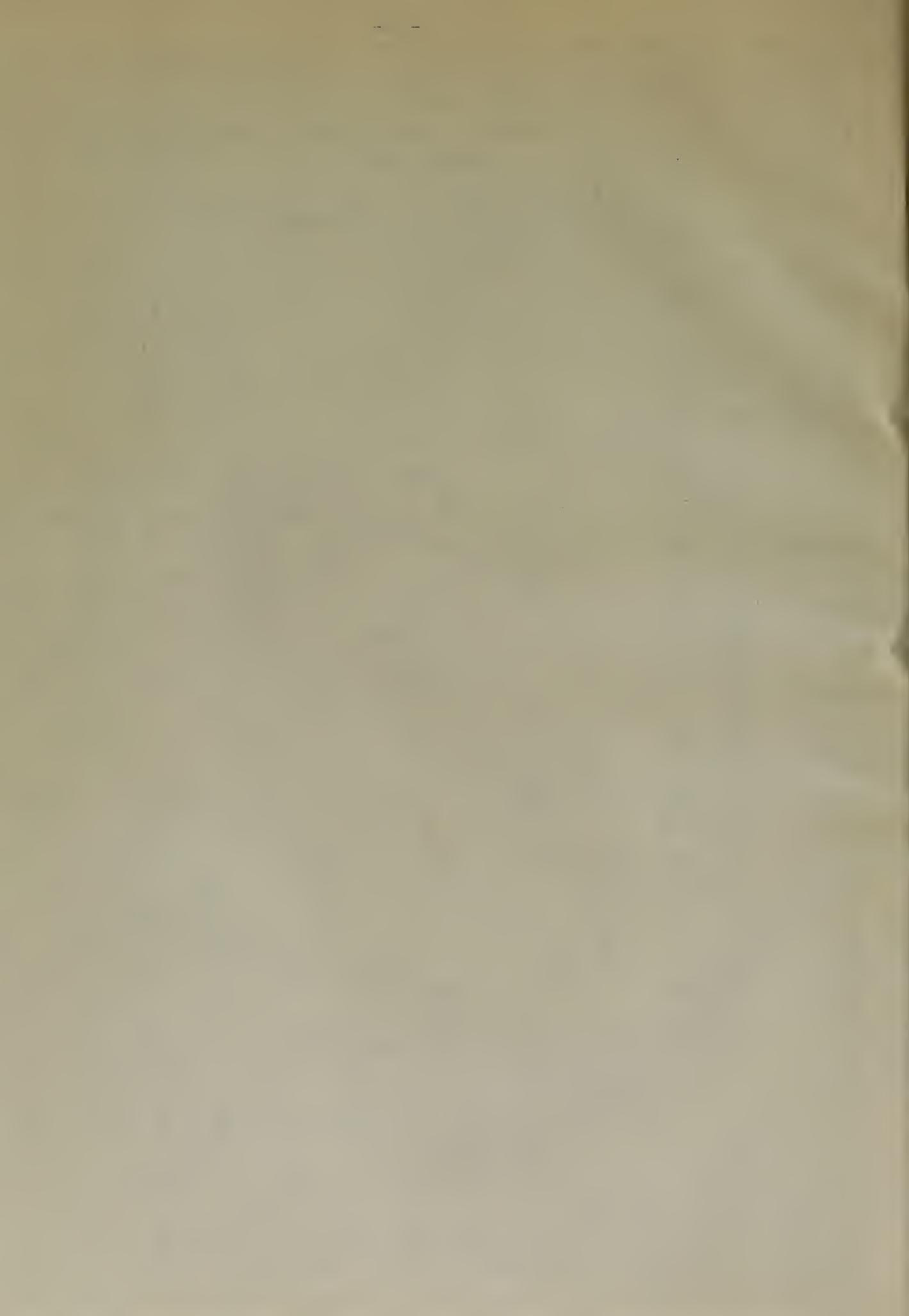
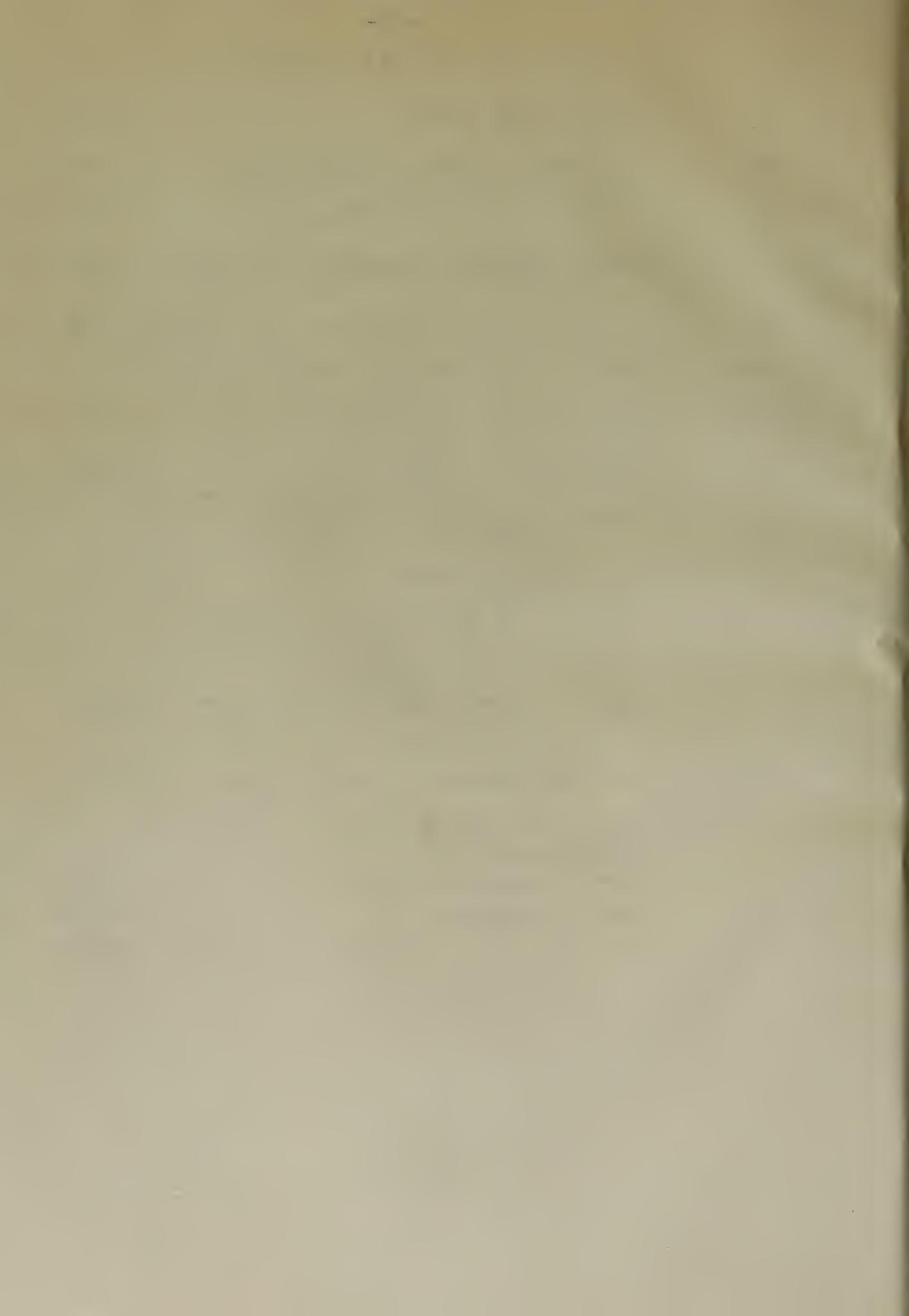


Fig. 19



NOMENCLATURE



BIBLIOGRAPHY AND REFERENCES

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- (3) Stewart, R. W.; "Literature Survey on the Use of Ceramic Materials for Turbine Blading." Allis-Chalmers Manufacturing Co., Turbine Development Department Report, 18 March, 1948.
- (4) McAdams, W. H.; "Heat Transmission;" 2nd Ed., McGraw-Hill Book Co., 1942.

DISCUSSIONS ON THEORETICAL

- ANALYSIS AND ITS APPLICABILITY 1. R. N. SARKARIA (1)
"THEORY OF POLYMER AND THE "POLYMER MODEL"
2. R. N. SARKARIA AND K. K. DASGUPTA 2. R. N. SARKARIA (2)
"THEORY OF POLYMER AND THE "POLYMER MODEL"
3. R. N. SARKARIA AND K. K. DASGUPTA 3. R. N. SARKARIA (3)
"THEORY OF POLYMER AND THE "POLYMER MODEL"
4. R. N. SARKARIA AND K. K. DASGUPTA 4. R. N. SARKARIA
"THEORY OF POLYMER AND THE "POLYMER MODEL"
5. R. N. SARKARIA AND K. K. DASGUPTA 5. R. N. SARKARIA
"THEORY OF POLYMER AND THE "POLYMER MODEL"
6. R. N. SARKARIA AND K. K. DASGUPTA 6. R. N. SARKARIA
"THEORY OF POLYMER AND THE "POLYMER MODEL"

SAMPLE CALCULATIONS

Air metering: With standard sharp edged orifice configuration with flange taps.

Cooling air,

$$w_a = .8595 K D_2^2 \frac{(P_2 + \Delta P)^{\frac{1}{2}}}{(T_a)^{\frac{1}{2}}} \quad (\text{ASME Power Test Code})$$

$T_a = 80^\circ \text{ F}$. Air supply temperature

$D_2 = .75"$ Orifice diameter

$D_1 = 2.07"$ Pipe diameter

$K = .61$ From Fig. 34(a) of ASME Power Test Codes

$P_2 =$ Absolute outlet static pressure
lb./in.²

$\Delta P =$ Orifice static pressure drop
lb./in.²

$$w_a = \frac{.8596 \times .61 \times (.75)^2}{(540)^{\frac{1}{2}}} (P_2 \times \Delta P)^{\frac{1}{2}}$$

$$\approx .01268 (P_2 \times \Delta P)^{\frac{1}{2}}$$

P	P(psi)	P_2	w_a (lb./sec.)	w_a (lb./min.)
.1	.0036	22.6	.00362	.217
.2	.0072	23.6	.00575	.345
.3	.0108	25.6	.00785	.471
.4	.0144	23.6	.01	.60
.5	.0180	50.6	.0121	.726
.6	.0216	57.6	.0141	.846
.7	.0252	64.6	.0162	.972
.8	.0288	71.6	.0182	1.09

Burner air,

$$w_{BA} = .8596 K D_2^2 \frac{(P_2 \times \Delta P)^{\frac{1}{2}}}{T_1^{\frac{1}{2}}}$$

$K = .704$

$D_2 = 5.6$

Results are tabulated in Tables I and II.

meilleur budget qu'aucun autre pays. L'opposition réclame que les dépenses publiques soient réduites.

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(What's your name?) John Smith (Age) 22

BRUNSWICK COUNTY, N.C., 1970.

Wadsworth's "Virtue" 23

2002-00001 2002-00002 (a)65 2002-00003 2002-00004

Avantages d'elles seules n'atteignent pas l'objectif.

զարգացնելու համար առաջին առաջարկը կատարվել է 1971 թ.

$$100\Delta = 10^3 \frac{0.0075 \times 10^3 \times 0.001}{0.0001} = 10^6$$

ANSWERED.

Country	Population	Rate	Deaths	Rate
U.S.A.	100,000,000	8.05	805,000	1.00
Germany	60,000,000	9.43	565,800	0.94
USSR	100,000,000	9.05	905,000	0.90
GB	50,000,000	9.09	454,500	0.90
NET.	70,000,000	9.00	630,000	0.86
Canada	30,000,000	9.29	278,700	0.93
SWZ.	900,000	9.63	86,700	0.96
W.C.I.	50,000,000	9.47	473,500	0.94

לעון רשות

卷之三

23 June 1997 we visited the localities near Lopar.

Mach. number:

$$q = \frac{\gamma}{2} P_{\infty}$$

M_4 = Test section mach. no.

q = Test section dynamic pressure

γ = 1.3 for gas

P_4 = Test section static pressure

$$M_4 = \frac{2q}{\gamma P_4} = \frac{q}{.65 P_4}$$

Results are tabulated in Tables I and II.

卷之三

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Li kue i wééhni ni Dzidzilwééh éétséézh

DATE DUE

27 MR '5

The Thesis
N4 N4

Ness

11472

Boundary layer control
as a method of gas tur-
bine blade cooling.

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